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1 A short-lived ²⁶Al induced hydrothermal alteration event in the

2 outer solar system: Constraints from Mn/Cr ages of carbonates

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4 Abstract

A key process in the early solar system that significantly affects the further evolution and transport of highly 5 6 volatile elements throughout the solar system hydrothermal parent body alteration. To determine whether hydrothermal alteration in outer solar system parent bodies occurred more or less simultaneously or due to 7 8 a sequence of multiple different events, we investigated low-temperature hydrothermally altered CM and CI chondrites along with volatile-rich CM-like clasts and C1 clasts with abundant mineral phases that contain 9 volatiles. In this respect, C1 clasts are particularly important as they closely resemble the CI chondrites but 10 11 originate from isotopically different parent bodies. Specifically, we applied the SIMS-based Mn/Cr in situ dating technique to carbonates, a common hydrothermally formed phase in low-temperature 12 13 hydrothermally altered meteorites. The Mn/Cr ages of dolomites in CI chondrites and C1 clasts as well as calcites in CM chondrites and CM-like clasts reveal that nearly all carbonates in low-temperature 14 hydrothermally altered clasts and chondrites were formed within a brief period between 2-6 Ma after CAI 15 formation. Given this sharp separation, and that hardly any material contains carbonates formed later than 16 ~ 6 Ma after CAI formation, hydrothermal alteration likely occurred near-contemporaneously among 17

different parent bodies in the outer solar system. Further, the timing of hydrothermal alteration matches 18 peak heating of ²⁶Al decay that ceased at ~5 Ma after CAI formation. Hereby, these results are consistent 19 with a model in which the carbonates in low-temperature hydrothermally altered parent bodies precipitated 20 21 from the fluid produced by melting ice. The results also show that other potential heating events (e.g., impacts) only negligibly contributed to creating environments where fluid-mediated dissolution and 22 precipitation of carbonates was possible. Additionally, the isotopic (H, O, Cr, and S) differences between 23 C1 clasts and CI chondrites are most likely not caused by differences in timing of hydrothermal aqueous 24 alteration and, thus, are best explained by spatially different isotopic reservoirs. 25

26 1. Introduction

The initial source, progression, and transport of water and other highly volatile components in the early 27 28 solar system is not yet fully understood, but clarifying these unknowns might provide information about parent body formation and solar system evolution. The first key process that influences how volatiles further 29 30 evolve and are transported throughout the solar system is parent body hydrothermal alteration, in which chemical components of accreted dust and ice are hydrothermally transformed into solid-bound volatile-31 rich phases (e.g., Sonett and Reynolds 1979; Prinn and Fegley 1989). These hydrothermally formed phases, 32 which occur in carbonaceous chondrites, especially CM and CI chondrites, are important carriers of highly 33 volatile elements from the outer to the inner solar system (Alexander 2017), and they also contain significant 34 35 information regarding the cause, duration, and extent of hydrothermal alteration in the outer solar system. Besides the CI and CM chondrites, other potential materials that can provide information on the evolution 36 and formation of hydrothermally formed phases are volatile-rich clasts. Volatile-rich CI- and CM-like clasts 37 occur in many different achondritic and chondritic meteorites and resemble CI and CM chondrites, 38 respectively (e.g., Wilkening 1973; Patzek et al. 2018a). These xenoliths occur as two principle types: C1 39 40 clasts and CM-like clasts. The C1 clasts bear strong resemblances to CI chondrites in terms of mineral composition and are composed of magnetite, Fe-Ni sulfides, carbonates (mainly dolomite), phosphates, and 41 42 remnants of chondrules, which are all embedded in a very fine grained serpentine/saponite matrix (e.g., Wilkening 1973; Brearley and Prinz 1992; Endress et al. 1994; Briani et al. 2009; 2012; Bonal et al. 2010; 43 Patzek et al. 2018a). A detailed study about the abundance of C1 clasts and the mineral chemical 44 45 compositions can be found in Patzek et al. (2018a). Furthermore, a study by Visser et al. (2018) shows

similarities between the peak temperatures experienced by C1 clasts and CI chondrites. This suggests, in 46 addition to the similarities in mineral composition, that CI chondrites and C1 clasts experienced comparable 47 formation environments. The secondary mineralogy of the clasts and chondrites implies pervasive aqueous 48 49 alteration at low temperatures (< 100 °C;). Even though, the mineralogy and peak temperatures of C1 clasts and CI chondrites are similar, recent studies show disparities between CI chondrites and C1 clasts in S, H, 50 51 and O isotope systems (Patzek et al. 2018b; 2019; Visser et al. 2019). These observations suggest that C1 clasts are fragments that originated from different parent bodies which sampled completely different isotope 52 reservoirs than those of CI chondrites. Therefore, this material may be crucial for determining whether 53 hydrothermal alteration was a relatively simultaneous event among outer solar system parent bodies or 54 whether it consisted of multiple different events. 55

The CM-like clasts, based on the mineralogy, can hardly be distinguished from CM chondrites and consist 56 of silicate chondrules with accretionary rims similar to those described in Metzler et al. (1992), carbonates 57 58 (mainly calcite), spinel, and sulfides. All these components are embedded in a fine-grained 59 serpentine/saponite matrix often dominated by tochilinite-cronstedtite intergrowths (TCIs) (e.g., Zolensky et al. 1996). Detailed mineral descriptions and chemical compositions of CM-like clasts were described in 60 61 Patzek et al. (2018a) The CM-like clasts have experienced similar peak temperatures to CM chondrites and suggest extensive aqueous alteration at low temperatures (Visser et al. 2018). Unlike the comparison of C1 62 63 clasts to CI chondrites, the CM-like clasts have almost identical S, H, and O isotopic compositions when compared to CM chondrites (Visser et al. 2019; Patzek et al. 2019; Patzek et al. 2018b). 64

65 Carbonates are among the hydrothermally formed phases with solid-bound volatiles that occur in parent 66 bodies of CM-like and C1 clasts as well as CI and CM chondrites. In order to better understand the hydrothermal alteration processes on the related parent bodies and especially the potential differences 67 68 between the different parental bodies, we aim to date hydrothermal activities by obtaining Mn/Cr ages of carbonates formed during the respective fluid-solid interaction. The Mn/Cr system is based on the electron 69 70 capture decay of radioactive 53 Mn into stable 53 Cr with a half-life (3.7 ± 0.4 Ma; Honda and Imamura, 1971) 71 making it a suitable method for dating dolomite ((CaMgCO₃)₂) and calcite (CaCO₃) formed within the first \sim 20 Ma years after the formation of the solar system (e.g., Lugmair and Shukolyukov, 1998; Shukolyukov 72 and Lugmair, 2006). 73

So far, several studies have investigated the hydrothermal formation ages of carbonates in CI, CR, C2_{ung} and CM carbonaceous chondrites (e.g., Endress et al. 1996; Hoppe et al. 2007; de Leuw et al. 2009; Fujiya et al. 2011; 2013; Jilly-Rehak et al. 2014; 2017). However, unlike other studies, in our study we analyze carbonates in a comprehensive dataset of CM and CI lithologies such as chondrites and lithic clasts in complicated breccias that sampled different parent bodies from the outer solar system. Ultimately, evaluating ages in materials that are seemingly similar but still represent different parent bodies potentially can constrain hydrothermal alteration in the outer solar system.

81 2. Methods

82 2.1 Sample selection

83 For determining the timing of the fluid-induced alteration event(s) in a comprehensive data set, we selected material that complemented already existing data in the literature. Two already dated CI chondrites were 84 85 analyzed and used as a benchmark. For the Mn and Cr measurements in carbonates a total of 13 different 86 thin section samples were selected from the Naturkunde Museum Berlin, Natural History Museum Vienna, 87 Westfälische Wilhelms-Universität Münster, and the NASA Johnson Space Center, Houston (Table 1 for details). Four C1 clasts in Kaidun (Cung), DaG 319 (ureilite), and Sahara 98645 (H3 chondrite) as well as a 88 total of ten CM-like clasts in Kaidun (Cung), PRA 04401, PRA 04402, NWA 7542A, and NWA 7542B (both 89 howardites) were selected for the analyses. Even though NWA7542A and B are the same sample but 90 91 different thin sections, they will be discussed separately. Additionally, carbonates within four different 92 carbonaceous chondrites, namely Ivuna, Orgueil, Alais (CI1) and LON 94101 (CM2) were chosen to serve as a comparison to those within the volatile-rich clasts as well as literature data. Carbonates in Murchison 93 94 (CM2) were only analyzed for their chemical composition and not for their Mn and Cr composition.

95 <u>TABLE 1</u>

96 2.2 Analytical details

97 To locate the carbonates in the five carbonaceous chondrites EDX scans of the whole sample surfaces were 98 performed with the JEOL JSM-6610LV scanning electron microscope at the Naturkunde Museum Berlin 99 for smaller C1 and CM-like clasts, individual EDX analyses were performed. The carbonates were then 100 analyzed for the element compositions of Ca, Cr, Mn, Mg, and Fe with a JEOL JXA 106 8200 Superprobe at the Freie Universität Berlin. A dolomite (Ca, Mg), Mn metal, Fe metal and Cr metal were used as standards
for the EMPA analyses and the detection limits of the elements reported in this study can be found in
Supplement 1A.

104 In total, 32 dolomites in Ivuna, Alais, and Orgueil as well as C1 volatile-rich clasts in Sahara 98645, DaG 105 319 and CI lithologies in Kaidun were deemed suitable for Mn/Cr dating. All related analyses were 106 performed with a CAMECA IMS 1280 large-geometry SIMS instrument at the NordSIMS facility, Swedish 107 Museum of Natural History Stockholm, Sweden. For these measurements, the stable isotopes ⁵⁵Mn, ⁵²Cr, 108 and 53Cr were analyzed. We used a high-brightness Oregon Physics-Hyperion RF-Plasma source to generate 109 a critically focused ¹⁶O primary beam of ca. 500 pA intensity with a spot size of \sim 3-4 µm. Prior to each 110 analysis an area of 10 by 10 µm was pre-sputtered for 180 seconds to remove the gold coating and any possible surface contamination. All measurements consisted of 100 cycles in which ⁵²Cr⁺ and ⁵³Cr⁺ were 111 detected simultaneously on two low-noise ion-counting electron multipliers for 20 seconds, with ⁵⁵Mn⁺ 112 113 measured for 2 seconds in the same detector as ${}^{53}Cr^+$ after a peak jump in each cycle. At the start of each 114 measurement the magnet B-field was centered on Mn to correct for any drift; the sample high voltage was scanned at the start and half-way through each analysis to maintain optimum energy distribution in the 45 115 116 eV energy window. The mass resolving power was \sim 4500 m/ Δ m for ⁵²Cr⁺ and 6500 m/ Δ m for ⁵⁵Mn⁺ and 117 ⁵³Cr⁺ to resolve the interferences from hydrides and Mg, Al, and Si combinations at nominal masses 52, 53, and 55. During measurements care was taken to detect sudden changes in ⁵³Cr/⁵²Cr ratios and count rates 118 that indicated that the primary beam had penetrated the carbonate grain, resulting in analysis of underlying 119 120 material. This only happened to a few calcite analyses, and these measurements were stopped and only used 121 in data processing if a minimal amount of cycles (~ 20) was reached.

Two reference materials were measured at regular intervals during the analytical sessions to correct for (1) instrumental mass fractionation and relative detector efficiency and (2) to determine the relative sensitivity factor (RSF) between the known and SIMS measured Mn/Cr ratio. For IMF and detector efficiency we used a San Carlos olivine, which has a homogenous, natural ⁵³Cr/⁵²Cr ratio. A synthetic calcite (Donohue et al. 2019), subsequently called "HIGP calcite" was used to determine the RSF for calcite and dolomite. Similar to other studies a calcite doped with Mn and Cr was used for RSF corrections (e.g., Siguira et al. 2010; Fuyija et al. 2013; Jilly-Rehak et al. 2017). However, due to the difficulty to produce this HIGP calcite

the Mn and Cr are heterogeneously distributed. The HIGP calcite is characterized by bright and dark areas 129 130 in BSE images, we visually selected relatively homogenous areas and analyzed these with exploratory EPMA analyses prior to the SIMS analyses. In general, the brighter areas contained more Cr and Mn compared to 131 132 the dark patches, and were therefore favored for SIMS analysis. After which the RSF calculations were 133 based on the average of four post-analytical electron microprobe analyses closely surrounding each analyzed 134 SIMS spots. This way, the Mn and Cr composition and thus the RSF for each SIMS analysis is very carefully 135 established and corrected for the heterogeneity of the standard and can be used with confidence. We are aware that the RSF values for the dolomite analyses might deviate from the RSF of calcite however, it is 136 137 currently not possible to create a reliable dolomite standard doped with Mn and Cr or to determine the RSF 138 differences between calcite and dolomite (e.g., Fuyija et al. 2013; Jilly-Rehak et al. 2017). We therefor acknowledge the fact that the Mn/Cr ages analyzed in dolomite can be compared with Mn/Cr ages of other 139 140 dolomite samples to give relative age constrains. The absolute Mn/Cr ages however might deviate slightly 141 due to the potential different RSF values of dolomite and calcite.

After these corrections and the rejection of measurements of insufficient quality, the corrected analyses were converted into an isochron; the isochron slope was used to calculate the Mn/Cr age. The anchor used for calculating the age was the D'Orbigny angrite (4563.37 \pm 0.25 Ma; Amelin 2008; Brennecka and Wadhwa 2012), and the relative ages were calculated as Ma "after CAI" (4567.2 \pm 0.31 Ma; Amelin et al. 2002). To ensure comparability, we recalculated all ages from the literature using this anchor and its ⁵³Mn/⁵³Cr ratio. All uncertainties are displayed in 2 σ notation throughout the manuscript and include uncertainties with respect to the RSF determination and individual measurements.

- 149
- 150

EQUATION 1

151 3. Results

152 The mineral chemical compositions of the carbonates are shown in a MgO+FeO-CaO-MnO ternary
153 diagram (Fig. 1). The whole dataset can be found in Supplement 1A (mineral chemical data) and Supplement
154 1B (Mn/Cr SIMS data).

155 3.1 Chemical compositions and textures of carbonates

156 In this study, two types of carbonates were identified. Calcite, is the dominant carbonate in CM material,157 whereas dolomite the foremost carbonate in CI and C1 material.

158 3.1.1 Calcite in CM type material

We specify CM-type material as being, CM chondrites, CM-like volatile-rich clasts, and CM lithologies in 159 160 Kaidun. The chemical composition of the calcites in these three materials is very similar, having almost pure 161 stoichiometric calcite composition (Fig. 1A). The Mn content in the calcites varies from 0 to 1 wt.%, but is 162 often below the detection limit of 0.04 wt.% Almost all calcites have Cr contents below the detection limit 163 of 0.03 wt.%. The grain sizes of calcite in the CM chondrites are generally between 20 and 50 µm. Calcite is 164 often rounded and has irregularly-shaped edges that can be fractured (Fig. 2A). Inside the CM-like clasts, 165 calcite looks similar in both chemical composition and appearance to the previously mentioned calcite in 166 CM chondrites (Fig. 2B and C). The calcite in CM-like clasts is similar in chemical composition, but is often 167 slightly smaller (10-30 µm). Nearly all calcite occurs in the matrix of the CM chondrites or CM-like clasts, 168 and only a few exceptions are located inside a chondrule or as an inclusion in a cluster of pyrrhotite laths (Fig. 2F). The latter, exhibits strong Mn zoning, with parts that contain up to four times the Mn as other 169 170 parts in the same carbonate, unlike other calcites in this study. The carbonates in this cluster are randomly-171 oriented, but they have smooth and round edges (Fig. 2F).

172 3.1.2 Dolomite in CI-type material

Dolomite is the dominant carbonate in C1 clasts and CI chondrites. In CI chondrites the sizes of the 173 174 dolomite vary among samples. In Ivuna and in the CI lithologies of Kaidun dolomite is generally large at 175 \sim 50 μ m in diameter and displays rounded shapes. In Orgueil and Alais, the dolomites often have fractures separating them from the porous matrix that were most likely caused by sample preparation methods. All 176 177 dolomites in the CI chondrites and Kaidun display a scratched or fractured surfaces. The dolomite is in 178 almost all cases embedded in the matrix and is divided by a sharp unaltered boundary (Fig. 2D). The majority 179 of the dolomite has a stoichiometric composition, and the Mn content of dolomite varies from ~1-5 wt.%. 180 Dolomite similar to that in CI chondrites is found in the CI lithology of Kaidun, but the dolomite in the C1 181 clasts of Sahara 98645 and DaG 319 are slightly different. Sahara 98645 contains one large dolomite (~100 182 μ m) that is located close to the boundary between the host rock and the C1 clasts (Fig. 2E). The dolomite 183 grain contains more Fe compared to dolomite in CI chondrites and the CI lithology in Kaidun and it has an

unusual shape, but it is texturally similar to the dolomite mentioned above. Dolomite in DaG 319 is in general similar to dolomite in other samples, but it is smaller (10-20 µm). In contrast to calcite, dolomite is capable of incorporating up to 5 wt.% Mn and 2 wt.% of Cr into its structure in CI chondrites, C1 clasts, and the CI lithologies.

188

FIGURE 1

189 3.2 ⁵³Mn/⁵⁵Mn isochrons

190 Instead of targeting a few grains that show exceptionally high Mn/Cr compositions, we analyzed almost all 191 calcites or dolomites, large enough for analyses, in each chondrite thin section or clast to generate sufficient 192 Mn/Cr data to define statistically meaningful isochrones. All slopes of the (⁵³Mn/⁵⁵Mn)₀ isochrons and 193 corresponding ages can be found in Table 2. All ⁵⁵Mn/⁵²Cr vs. ⁵³Cr/⁵²Cr isochrons can be found in 194 Supplement 2, an example diagram is shown in Figure 3.

195 3.2.1 Calcite in CM type material

196 We successfully analyzed 18 calcite grains in LON 94101 with the SIMS, and several of these calcite grains 197 yielded substantially high Mn/Cr ratios to resolve an isochron. The slope of the isochron is defined by the $({}^{53}Mn/{}^{55}Mn)_0$ ratio of 4.80 x 10⁻⁶ ± 6.60 x 10⁻⁶ with a maximum ${}^{52}Cr/{}^{55}Mn$ of ~13,000. PRA 04401 and 198 199 04402 are howardites and contain 29 calcites, of which 20 were analyzed. They are distributed over several 200 clasts located on different thin sections. The individual (53Mn/55Mn)₀ slopes for PRA 04401 and PRA 04402 are 6.53 x 10⁻⁶ and 1.40 x 10⁻⁶, with a maximum ${}^{52}Cr/{}^{55}Mn$ of ~8,000 and 4,000, respectively. The calcite 201 202 isochron of the CM-like clast in howardite NWA 7542A has a $(^{53}Mn)^{55}Mn)_0$ ratio of 2.02 x $10^{-6} \pm 6.40$ x 10^{-6} 203 ⁶ with a maximum ⁵²Cr/⁵⁵Mn of ~6,500. In Kaidun, 26 grains in one particular CM1 lithology reveal a $({}^{53}Mn/{}^{55}Mn)_0$ slope of 3.44 x 10⁻⁶ ± 6.20 x 10⁻⁷ with an extremely high maximum ${}^{52}Cr/{}^{55}Mn$ of ~170,000. 204

205

FIGURE 2

206 3.2.2 Calcite in CI and C1 type materials

207 The CI chondrites, Ivuna, Alais, and Orgueil have ${}^{53}Mn/{}^{55}Mn$ ratios of 2.78 x 10⁻⁶ ± 5.10 x 10⁻⁷, 3.68 x 10⁻² 208 6 ± 6.40 x 10⁻⁷, and 3.13 x 10⁻⁶ ± 8.40 x 10⁻⁷, respectively, and maximum ${}^{52}Cr/{}^{55}Mn$ ratios of ~55,000, 209 ~12,000, and ~5,000, respectively. A similar result is found for the CI lithology in Kaidun, which has a (⁵³Mn/⁵⁵Mn)₀ ratio of 2.89 x 10⁻⁶ ± 4.10 x 10⁻⁷ with a maximum of ~20,000. Unlike the CI chondrites and
the CI lithology in Kaidun, the C1 clast in the DaG 319 ureilite and the C1 clast in the H3 chondrite Sahara
98645 show negative (⁵³Mn/⁵⁵Mn)₀ ratios of -3.41 x 10⁻⁶ ± 4.30 x 10⁻⁶ and -7.78 x 10⁻⁶ ± 7.30 x 10⁻⁶,
respectively. The (⁵³Mn/⁵⁵Mn)₀ ratios have relatively high uncertainties and are also characterized by lower
⁵²Cr/⁵⁵Mn ratios (⁵²Cr/⁵⁵Mn DaG 319: 600, ⁵²Cr/⁵⁵Mn Sahara 98645: ~700) compared to those of the CI
chondrites and the CI lithology in Kaidun.

216

TABLE 2

217 4. Discussion

In order to clarify whether the determined Mn/Cr ages of the individual samples are indeed related to early alteration processes on the respective early formed parent bodies, we discuss the data in context of various aspects such as terrestrial weathering and carbonate textures, which will help explain the similarities and differences between the ages of the different samples as well as from the literature (e.g., Endress et al. 1996; Hoppe et al. 2007; de Leuw et al. 2009; Fujiya et al. 2011; 2013; Jilly-Rehak et al. 2014; 2017).

- 223
- 224

FIGURE 3

225 4.1 Age determination and literature comparison

To determine the absolute ages, we have anchored the $({}^{53}Mn/{}^{55}Mn)_0$ ratios obtained in this study to the (${}^{53}Mn/{}^{55}Mn)_0$ ratio of 3.54 x 10⁻⁶ ± 1.80 x 10⁻⁷ (McKibbin et al. 2015) which has been correlated to the U isotope-corrected Pb-Pb ages of the D'Orbigny angrite (4563.37 ± 0.25 Ma; Amelin 2008; Brennecka and Wadhwa 2012). The D'Orbigny angrite was chosen because it is one of the oldest rocks and has been dated with multiple radiometric systems, a detailed discussion for this decision can be found in Jilly-Rehak et al. (2017). Additionally, all ages will also be displayed relative to the formation of CAIs (4567.2 Ma; Amelin 2002).

We analyzed the complete carbonate inventory possible with the spatial resolution used to get the most
accurate isochrons possible, whereas other studies generally analyze limited amount of highly ⁵³Cr enriched
carbonates per sample. The Mn/Cr ages of the samples analyzed in our study will be compared to literature
(e.g., Fujiya et al. 2011; 2013; Jilly-Rehak et al. 2014; 2017). Studies (e.g., Endress et al. 1996; Hoppe et al.

237 2007; de Leuw et al. 2009) that published Mn/Cr ages using glass or San Carlos standards will not be
238 discussed since the different RSF between standards and carbonates overestimate the ⁵³Mn/⁵⁵Mn ratios and
239 result in significantly older inferred ages (Sigiura et al. 2010; Jilly-Rehak et al., 2017).

240 Carbonates within the three CI chondrites Ivuna (4562.1 $^{0.9}/_{1.1}$ Ma), Alais (4563.6 $^{0.9}/_{1.0}$ Ma), and Orgueil 241 (4562.7 $^{1.3}/_{1.7}$ Ma), have ages that are very similar to one another. They are also coherent with the ages 242 obtained for carbonates CI chondrites analyzed by Fujiya et al. (2013) (Fig. 4).

243 Kaidun is an interesting sample since it represents a complicated breccia with different CI, CM, and even 244 enstatite chondrite lithologies (Ivanov 1989; Zolensky and Ivanov 2003). Petitat et al. (2011) analyzed three 245 dolomite grains in two different CI lithologies in Kaidun using NBS 611 glass and San Carlos olivine as 246 standards. Recent studies showed that the RSF between San Carlos and a calcite differ significantly, which 247 means that the current ages of the CI lithology in Kaidun, might be inaccurate (Sigiura et al., 2010). We therefore analyzed a CI and CM lithology in Kaidun with the new HIGP calcite standard. In this study, we 248 249 made a clear distinction between CM and C1 clasts to determine possible age differences of two different lithologies in one sample. We analyzed 16 dolomites in the C1 clast and 26 calcites in the CM-like clast of 250 Kaidun which yielded ages very similar to one another. The dolomites in C1 clasts have an age of 4562.3 251 $^{0.7}/_{0.8}$ and the calcites in the CM-like clasts yields an age of 4563.2 $^{0.8}/_{1.1}$ with a maximum $^{52}Cr/^{55}Mn$ of 252 17,000 and 160,000, respectively. This shows that the ages obtained for the different lithologies in Kaidun 253 254 are similar to one another and are consistent with the Mn/Cr ages of CM and CI chondrites (Fig. 4). The 255 difference in age of the CI lithologies in our study and of that in Petitat et al. (2011), might be a direct result 256 of the inaccurate RSF used in Pepitat et al. (2011). Despite the relatively small age difference with the 257 different standard it indicates the increased reliability of our data due to the larger number of measurements and more appropriate RSF. The lithic clasts mentioned in van Kooten et al. (2016) have strong similarities 258 259 with the C1 clasts in this study. The Mn/Cr age of these clasts analyzed by van Kooten et al. (2016) agree well with Mn/Cr ages obtained for CI chondrites and lithologies in our study as well as from literature. 260

261 The Mn/Cr data of the three samples LON 94101 (4565.0 ^{4.6}/_{4.7} Ma), NWA 7542A (4560.4 ^{7.6}/_{7.0} Ma), PRA
262 04401 (4566.6 ^{2.6}/_{5.3} Ma), reveal considerably larger uncertainties compared to the samples above mentioned.
263 These larger uncertainties reflect the very low counts of Mn and Cr during the analyses. Even though the
264 analyses are not very accurate, they largely agree with those obtained for other analyzed samples and

265 literature data (Fig. 4). PRA 04402 (4558.4 ^{9.4}/_{9.2} Ma) contains even larger uncertainties and is therefore not
266 displayed in the figures nor discussed further.

Even though all clasts that were analyzed contain significant enrichments in ⁵⁵Mn over ⁵²Cr, not all samples have ${}^{53}Cr/{}^{52}Cr$ ratios that are elevated compared to the present day ratio of 0.113459 \pm 0.000005 (Papanastassiou 1986). None of the carbonates inside C1 clasts in DaG 319 and Sahara 98645 are enriched in ${}^{53}Cr$ (Supplement 1B), making it impossible to calculate their formation ages.

In general, the obtained Mn/Cr ages in the studied chondrites (CM, CI, C2_{ung}, and CR) and clasts (CM-like and C1) fall in a relatively small, distinct range clustering around $\sim 4 \pm 2$ Ma after the formation of CAIs (Figs. 3 and 4). This indicates that the hydrothermal alteration event, or at least the fluid-mediated precipitation of the dolomite and calcite in CM and CI chondrites and the clasts, occurred in approximately the same time period for all investigated low temperature heavily-altered parental bodies.

276

FIGURE 4

277 4.2 Hydrothermal alteration induced formation of carbonates.

278 Nowadays it is a widely-accepted that after the accretion of ice and dust into kilometer-sized parent bodies, the heat produced by ²⁶Al decay caused ice to melt (Sonett and Reynolds 1979; Prinn and Fegley 1989). Due 279 280 to the short half-life of the ²⁶Al/²⁶Mg radioactive system (0.72 Ma; Lee et al. 1976) this heating was short-281 lived, ceasing roughly 5 Ma after the formation of CAIs (Fig. 5) In this short time period, the fluid produced 282 by the melting of ice altered the primary material to various different degrees (Sonett and Reynolds 1979; 283 Prinn and Fegley 1989). Whereas CI chondrites and also the C1 clasts have been heavily altered, indicated 284 by the presence of abundant secondary minerals (e.g., phyllosilicates) and the lack of primary features 285 (chondrules), the CM chondrites and CM-like clasts were also aqueously altered, but not as rigorously and 286 still maintained abundant chondrules with accretionary rims (Zolensky and McSween 1988). The majority 287 of the carbonates analyzed in our study and in literature all formed in a narrow time interval from 2-6 Ma. 288 This observation confirms that the carbonates were of secondary origin and formed during the time period in which ²⁶Al decay was the main heat source, as was also suggested by Fujiya et al. (2013). 289

290 Further, the latest estimated peak metamorphic temperatures obtained by Visser et al. (2018) suggest that,
291 similar to most CI and CM chondrites (DuFresne and Anders, 1962; Clayton and Mayeda, (1999); Alexander
292 et al. 2015; Verdier-Paoletti et al. 2017), C1 clasts and CM-like clasts studies here have not experienced

temperatures higher than ~100 °C. Some CM chondrites do however, show evidence for higher 293 temperatures (Alexander et al. 2015; Verdier-Paoletti et al. 2017; Vacher et al. 2019). The temperatures 294 295 obtained by Visser et al. (2018) are of particular interest since the temperatures were established on the same 296 samples that are being used here (for details see Visser et al. 2018; and references therein). It hereby seems 297 that no evidence of impacts were observed in the samples used in this study (chondrule flattening) which is 298 a first hint to why impact heating did not play a role in the carbonate-forming process of the carbonates 299 studied in this manuscript and literature data used. Moreover, particularly impacts into small kilometer-sized 300 porous parent bodies likely could not create conditions in which temperatures under 100 °C were maintained 301 for longer periods of time, thus creating an environment in which fluid-mediated dissolution and 302 precipitation processes were able to generate carbonates. Another argument against carbonates being 303 formed by impact-triggered processes is that so far no CI and/or CM type material contained carbonates 304 formed from ~10-25 Ma after CAI formation. In fact, if impact-triggered processes were responsible for 305 forming carbonates, this should have resulted in a significantly broader age distribution, which is directly 306 opposite to what we have found (including Petitat et al. 2011; Fujiya et al. 2011; 2013; Jilly-Rehak et al. 2014; 307 2017). This means that the carbonates in low-temperature altered carbonaceous chondrite and clasts in this 308 study formed during one main, near-contemporaneously, ²⁶Al decay induced hydrothermal alteration event 309 at 2-6 Ma after CAI formation throughout the outer solar system (Figs. 3 and 4).

310 4.3 Absence of ⁵³Mn during carbonate formation

The lack of ⁵³Cr, and therefore the inability to establish an age for the C1 clasts in DaG 319 and Sahara 98645, could be due to various reasons. All the carbonates evidently formed at a time, when no or very little ⁵³Mn could be incorporated, which might have occurred via four different scenarios: i) late formation of the carbonates in parent bodies after the ⁵³Mn decay system was extinct, ii) late formation of carbonates due to the interaction with the host rock, iii) terrestrial formation origin, or iv) heterogeneous distribution of ⁵³Mn in the parent bodies. Each scenario is discussed in detail below.

317

FIGURE 5

318 i) Late formation by hydrothermal processes of clasts and chondrites

319 In this particularly scenario the absence of ⁵³Cr has to be a result of a late formation of carbonates in the320 precursor parent bodies of the clasts. This would mean that the dolomite in the two C1 clasts and the calcite

in the CM-like clasts were formed at least 20 Ma after the carbonates in CM and CI chondrites (Fig. 5) when
the ⁵³Mn decay system was extinct and, therefore no ⁵³Mn excess was present to be incorporated during
carbonate formation. This scenario is supported by the fact that dolomites in CI chondrites and C1 clasts
are chemically and microstructurally similar and do not show any textures that may point to late
recrystallization processes.

326 Visser et al. (2018) used Raman thermometry, with an automated peak fitting method, of matrix carbon 327 embedded in a high quantity of CM- and CI-type materials to determine the peak temperatures obtained by 328 various chondrites, CM-like clasts, and C1 clasts. They suggested that the 26Al decay heated the parent bodies to ~100 °C, starting the hydrothermal alteration by melting ice. Vacher et al. (2019) suggested that two 329 different types of carbonates can be distinguished (T1 and T2) which formed at different temperatures. The 330 331 temperature difference could mean that the different types of carbonates formed location with small 332 temperature differences or they might have slightly different formation ages. It is however, unlikely that that 333 age different would be significant, due to the relatively small temperature differences and the inability of 334 small parent bodies to retain heat. Visser et al. (2018) also deemed it unlikely that the material was re-heated 335 by impacts, because there is no evidence for shock, or intense heating. Due to the porous and volatile-rich 336 nature of the material, a high velocity impact would have exploded and thus obliterate the material on impact 337 (Scott et al. 1992). It is, therefore, doubtful that at such a stage an environment could be established suitable 338 for dissolution and precipitation by circulating fluids to produce the carbonates. While some CM chondrites 339 do show evidence of impacts or excessively high heating, these instances are rare and serve more as 340 exceptions rather than the rule (e.g., Lunning et al. 2016). It might be interesting for future research to 341 determine ages of similar matrix carbonates (if present) in these rare CM chondrites that show impact-342 related features (e.g., chondrule-flattening, shock veins) to determine whether the carbonates in these 343 samples have Mn/Cr ages similar to the ages presented in this study of whether they formed by impacts (> 344 25 Ma after CAI formation).

345

346 If we assume that ²⁶Al decay was the only significant heating process of the parent bodies of the C1 and
347 CM-like clasts' parent body, the heating concluded roughly ~5 Ma after CAI formation (Fig. 4). Within that
348 time, parent bodies were warm enough to accommodate fluids from which carbonates precipitated. Without

another heating source, it is unlikely the parent bodies would have remained warm enough for another ~20
Ma to accommodate necessary fluids from which carbonates could precipitate after the ⁵³Mn/⁵³Cr system
was extinct (Fig 5). Furthermore, the narrow time range in which most CI, CM, and CR chondrites fall, as
well as lithologies in Kaidun, suggest that there was only a brief timespan, when the conditions were suitable
to precipitate carbonates from a fluid.

354 Countering this idea, Jilly-Rehak et al. (2017) found calcites in CR chondrite GRO 95577 with a significantly 355 younger age (~4553 Ma) than other CM, CI, and CR chondrites discussed in literature (~4563 Ma; Petitat 356 et al. 2011; Fujiya et al. 2011; 2013; Jilly-Rehak et al. 2014; 2017; this study). They suggested that the calcites 357 younger age is caused by either the parent body's ability to better retain heat in the late stages of ²⁶Al decay 358 or re-heating by impacts. Nonetheless, this shows that there might be exceptions, in which a suitable 359 environment is prolonged to precipitate carbonates relatively late. Then again, the calcite in GRO 95577 did 360 not form late enough to have a ⁵³Cr/⁵²Cr similar to the present day ratio; thus, this indicates that certain 361 parent bodies might have experienced additional heating from other sources. In our case this is unlikely due 362 to the exceptionally large time difference and also because the mineral compositions of the C1 and CM-like 363 clasts and CI and CM chondrites are so similar suggesting that they had similar environments and formation 364 histories.

365 ii) Hydrothermal formation of carbonates in C1 clasts by incorporation into the host

366 The second possible scenario is that dolomites in DaG 319 and Sahara 98645 formed or recrystallized during 367 thermal or fluid-mediated interaction with the host rock. Yet, with the mineralogy and temperature data 368 gathered in Patzek et al. (2018a) and Visser et al. (2018), there is no reason to assume that there was any 369 (thermal) interaction with the hosts. Even though ureilites formed at high temperatures (>1000 °C; Sinha 370 et al., 1997), the incorporation of the clasts happened after the host had completely cooled. Additionally, 371 we found that neither a C1 clast in a ureilitic host (DaG 319) nor a C1 clast in an unheated H3 chondrite host (Sahara 98645) had enough ⁵³Cr enrichments to calculate an age. This indicates that the absence of 372 373 ⁵³Mn was not caused by a recrystallization event triggered after incorporation in the host rock.

374 iii) Terrestrial formation of carbonates in chondrites and clasts

375 Another potential scenario is that the dolomite in C1 clasts underwent recrystallization during terrestrial

376 weathering. One strong indicator pointing to this possibility is that the clasts for which ages were not

established are desert finds. Their related host rocks often show weathering features (e.g., Sahara 98645),
and chemical disturbances (Stelzner et al. 1999). While previous studies have shown that terrestrial calcite
veins can form even in samples that are retrieved quickly after they fell (e.g., Bland et al. 2006) these veins
were not observed in the close proximity of the analyzed clasts. Additionally, we only analyzed carbonates
embedded in the matrix of the clast and do not recognize any microstructures that could or would indicate
terrestrial formation, however, this cannot completely be ruled out.

383 iv) Small scale heterogeneous distribution of ⁵³Mn in the parent bodies

In the combined studies of Patzek et al. (2018a) and Visser et al. (2018; 2019) and in this study more than 100 volatile-rich CM-like and C1 clasts have been categorized. Unfortunately, out of roughly 80 studied C1 clasts only two, analyzed in this study, had sufficient suitable carbonates for in situ Mn/Cr analyses. When we consider all of the above-mentioned limitations, it is unlikely that the carbonates in C1 clasts were formed after the ⁵³Mn/⁵³Cr system was extinct or by recrystallization processes.

The final scenario, to explain the ⁵³Mn depleted carbonates in C1 clasts, is small-scale heterogeneous distribution of Mn and Cr in local domains within parent bodies. Carbonaceous chondrites in general and especially CI and CM chondrites are often breccias, consisting of slightly different lithologies that might have had slightly different chemical compositions (e.g., Fuchs et al. 1973; Metzler et al. 1992; Metzler 1995; Morlok et al. 2006; Bischoff et al. 2006, 2017; Alfing et al. 2019). Even within the same meteorite, local domains with varying abundances of magnetite and sulfides indicate small-scale heterogeneities within fluid compositions and conditions responsible for the hydrothermal alteration (Alfing et al. 2019).

Even though we find localized differences in these carbonates, we assume that the Mn/Cr ratios lead back to an initial ratio and that ⁵³Mn was homogenously distributed throughout the solar system (Fig. 6). The formation of phases, that have different compatibility for Mn and Cr, leads to fractionation of the Mn/Cr ratio, which, by the time of hydrothermal alteration, will result in phases with different elemental and isotopic compositions. The main processes that can influence this fractionation and hereby isotopic Mn and Cr ratios, from which the hydrothermally formed carbonates precipitated are illustrated in Figure 6 and described in the following: The abundance and distribution of specific phases with different Mn/Cr ratios can lead to local
 domains with differences in Mn and Cr concentrations. This directly affect the availability of ⁵³Mn,
 ⁵³Cr, ⁵⁵Mn, and ⁵²Cr in the environment from which the carbonate precipitates.

406 - The solubility of phases control Mn and Cr concentrations released during dissolution. In relative
407 short amounts of time carbonates can precipitate from a fluid with different concentrations of Mn
408 and Cr caused by a sequential hydrothermal alteration of phases that have different solubilities.

The fluid-mediated connectivity within the system (size of local domain vs interaction of local domains) may lead to variable degrees of mixing, either equilibrating the Mn/Cr ratios to bulk
values or maintain chemically separate domains in which Mn/Cr ratios differ from one another.
Additionally, the connectively is directly related to the fluid-rock interaction. The ratio among these
Mn-Cr bearing phases and ice can lead to domains affected by different degrees of fluid-rock
interaction.

The interplay between the small-scale localized domains with differences in availability of Mn and Cr caused by the before mentioned processes that directly influence ⁵³Mn/⁵⁵Mn and ⁵⁵Mn/⁵²Cr ratios is in agreement with localized fluid flow of 100s of μm suggested by Bland et al. (2009). The abundances of carbonates with specific ⁵³Cr/⁵²Cr ratios in one particular clast or lithology depend on the scale and abundance of the different domains as well as the timing when the carbonate formed. It is therefore plausible that carbonates in the two C1 clasts precipitated in domains where the fluid contained low ⁵⁵Mn/⁵²Cr and ⁵³Cr/⁵²Cr ratios.

- 421
- 422

FIGURE 6

- 423
- 424

425 5. Conclusion

426 Given the sharp age boundary defined by our dataset, and taking into account literature Mn-Cr ages of low427 temperature aqueously altered carbonaceous chondrites, we can conclude that the carbonates precipitated
428 from a fluid affected environment generated by the ²⁶Al decay-induced melting of ice. We also suggest that

429 impact heat, if it was generated at all in our samples, did not create suitable thermodynamic environments430 for the formation of carbonates.

431 Ages of volatile-rich clasts that could not be established were most likely a result of sampling bias and small-432 scale localized heterogeneities in the concentration of Mn and Cr at the time of carbonate formation. We 433 deem it unlikely that the lack of ⁵³Mn enrichments occurred because (i) carbonates formed late when the 434 ⁵³Mn system was extinct (after 25 Ma) (ii) the clasts interacted with their hosts (iii) impact heating or (iv) 435 terrestrial alteration.

436 Previous isotopic studies of volatile-rich clasts suggested that CM-like clasts and CM chondrites are most 437 likely similar materials, whereas C1 clasts and CI chondrites sampled different isotopic reservoirs. The 438 differences in these isotopic systems are, according to our results, not caused by differences in the related 439 hydrothermal processes between the C1 clasts and CI chondrites, as the temperature condition and the 440 timing has been almost identical. An explanation for this might be spatially different reservoirs; however, as 441 of yet we cannot exclude other possible mechanisms.

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- 579

580 Equations, Table, and Figure captions

581 Eq. 1: 53Mn/53Cr age calculation using D'Orbigny as an anchor.

582
$$\Delta \tau = \frac{1}{\lambda} * \ln \left(\frac{\left[\frac{(5^3 M n)}{(5^5 M n)} \right]_{anchor}}{\left[\frac{(5^3 M n)}{(5^5 M n)} \right]_{sample}} \right)$$

Fig. 1: CaO-MgO+FeO-MnO ternary diagram of the carbonates in CM chondrites and CI chondrites
(A,) and C1 clasts and CM-like clasts (B). Dolomite can contain up to 5 wt.% Mn, whereas calcite
generally has a maximum of 1% wt.% Mn.

586

Fig. 2: BSE images of calcite and dolomites found in this study. A) Fractured calcite in the CM
chondrite LON 94101. B and C) Calcite grains in CM-like clasts quite similar to the calcite in the CM
chondrites. D) A dolomite mineral in the CI chondrite Ivuna. E) A large dolomite in the C1 clasts found
in the H3 chondrite Sahara 98645. F) Dolomite capsuled inside a large pyrrhotite cluster in a C1 clast
of Kaidun.

592

Fig. 3: 55Mn/52Cr vs. 53Cr/52Cr diagram of dolomites in CI chondrite Ivuna with a calculated age of4562.8 Ma.

595

Fig. 4: Absolute Mn/Cr ages chondrites in literature and CM and CI chondrites and clasts in this study
are displayed with a 2σ uncertainty. Literature data (circles) have been added from A) Fujiya et al.
(2013), B) Fujiya et al. 2011, C) Jilly-Rehak et al. (2014), D) Jilly-Rehak et al. (2017), E) Pepitat et al.
(2011), and F) van Kooten et al. (2016).

600

Fig. 5: Visualization of the Mn/Cr data in CM, CI, C2ung, and CR chondrites from literature and this study as well as volatile-rich clasts in the early stages of the solar system. The narrow distribution of CM chondrites, CI chondrites, CM-like clasts, and C1 clasts corresponds very well with the expected fluid release from ice by 26Al decay (red curve) heating in the first ~5 Ma after CAI formation. The 53Mn decay (green curve) is active until roughly 25 Ma after CAI formation. It is unlikely that parent bodies retained their heat or were reheated by impacts after 20 Ma years of the aqueous alterationevent to be able to form carbonates without 53Mn.

608

609 Fig. 6: Within a parent body, the heterogeneous compaction of ice and varying phases (t-1) result in areas with different pore space densities (A1 and A2), phase abundancies (B1 and B2), and the 610 611 connectivity. During hydrothermal alteration, the small-scale variations of Mn and Cr isotopes in the fluid are controlled by the abundancy and solubility of phases as well as the connectivity of local 612 domains. Carbonates formed in an area with abundant hydrothermally altered phase A (dark blue 613 614 carbonate formed at t-2) can ultimately have significantly different 53Cr/52Cr ratio compared to carbonates (green and red carbonates) formed at different times and domains where phase B or C 615 delivered the Mn/Cr ratios to the fluid (t3 and t4). Ultimately, the carbonates formed in the 616 617 heterogeneous domains make up an isochron it is possible that due to sampling bias we analyzed the 618 carbonates in C1 clasts formed in domains that resulted in low 53Cr/52Cr and 55Mn/52Cr ratios.

619

Table 1: Specifications of the samples used in this study, the number of clasts analyzed in these
samples (when applicable), the number of carbonates that were analyzed and identified by EMPA,
and the number of SIMS analyses used to produce the isochrons.

623

Table 2: Type, 53Mn/55Mn ratio, and age for the individually analyzed samples but also for
combined samples such as the Kaidun CM lithology (measured over two sessions), NWA 7542A and B
which are different thin sections of the same meteorite, and the linked howardite PRA04401 and
04402.

628

$$\Delta \tau = \frac{1}{\lambda} * \ln \left(\frac{\left[\frac{(5^3 M n)}{(5^5 M n)} \right]_{anchor}}{\left[\frac{(5^3 M n)}{(5^5 M n)} \right]_{sample}} \right)$$

Eq. 1: ${\rm ^{53}Mn}/{\rm ^{53}Cr}$ age calculation using D'Orbigny as an anchor.



Fig. 1: CaO-MgO+FeO-MnO ternary diagram of the carbonates in CM chondrites and CI chondrites (A,) and C1 clasts and CM-like clasts (B). Dolomite can contain up to 5 wt.% Mn, whereas calcite generally has a maximum of 1% wt.% Mn.



Fig. 2: BSE images of calcite and dolomites found in this study. A) Fractured calcite in the CM chondrite LON 94101. B and C) Calcite grains in CM-like clasts quite similar to the calcite in the CM chondrites. D) A dolomite mineral in the CI chondrite Ivuna. E) A large dolomite in the C1 clasts found in the H3 chondrite Sahara 98645. F) Dolomite capsuled inside a large pyrrhotite cluster in a C1 clast of Kaidun.



Fig. 3: ⁵⁵Mn/⁵²Cr vs. ⁵³Cr/⁵²Cr diagram of dolomites in CI chondrite Ivuna with a calculated age of 4562.8 Ma.



Fig. 4: Absolute Mn/Cr ages chondrites in literature and CM and CI chondrites and clasts in this study are displayed with a 2σ uncertainty. Literature data (circles) have been added from A) Fujiya et al. (2013), B) Fujiya et al. 2011, C) Jilly-Rehak et al. (2014), D) Jilly-Rehak et al. (2017), E) Pepitat et al. (2011), and F) van Kooten et al. (2016).



Fig. 5: Visualization of the Mn/Cr data in CM, CI, $C2_{ung}$, and CR chondrites from literature and this study as well as volatile-rich clasts in the early stages of the solar system. The narrow distribution of CM chondrites, CI chondrites, CM-like clasts, and C1 clasts corresponds very well with the expected fluid release from ice by ²⁶Al decay (red curve) heating in the first ~5 Ma after CAI formation. The ⁵³Mn decay (green curve) is active until roughly 25 Ma after CAI formation. It is unlikely that parent bodies retained their heat or were reheated by impacts after 20 Ma years of the aqueous alteration event to be able to form carbonates without ⁵³Mn.



Fig. 6: Within a parent body, the heterogeneous compaction of ice and varying phases (t_1) result in areas with different pore space densities (A1 and A2), phase abundancies (B1 and B2), and the connectivity. During hydrothermal alteration, the small-scale variations of Mn and Cr isotopes in the fluid are controlled by the abundancy and solubility of phases as well as the connectivity of local domains. Carbonates formed in an area with abundant hydrothermally altered phase A (dark blue carbonate formed at t_2) can ultimately have significantly different ${}^{53}Cr/{}^{52}Cr$ ratio compared to carbonates (green and red carbonates) formed at different times and domains where phase B or C delivered the Mn/Cr ratios to the fluid (t_3 and t_4). Ultimately, the carbonates formed in the heterogeneous domains make up an isochron it is possible that due to sampling bias we analyzed the carbonates in C1 clasts formed in domains that resulted in low ${}^{53}Cr/{}^{52}Cr$ and ${}^{55}Mn/{}^{52}Cr$ ratios.

Meteorite	Meteorite type	No. clasts analyzed	No. carbonates	No. SIMS analyses				
Carbonaceous chondrites								
Ivuna	CI chondrite	-	18	9				
Orgueil	CI chondrite	-	4	6				
Alais	CI chondrite	-	10	16				
Murchison	CM chondrite	-	21	-				
LON 94101	CM chondrite	-	22	18				
C1 clasts								
DaG 319	Ureilite	1	6	7				
Sahara 98645	H3	2	3	5				
Kaidun-2	C _{ung} chondrite	1	20	16				
CM-like clasts								
PRA04401	Howardite	2	19	13				
PRA04402	Howardite	3	10	7				
NWA7542A	Eucrite p-mict	2	14	13				
NWA7542B	Eucrite p-mict	2	5	6				
Kaidun-1	C _{ung} chondrite	1	21	26				

Table 1: Specifications of the samples used in this study, the number of clasts analyzed in these samples (when applicable), the number of carbonates that were analyzed and identified by EMPA, and the number of SIMS analyses used to produce the isochrons.

Table 2: Type, ⁵³Mn/⁵⁵Mn ratio, and age for the individually analyzed samples but also for combined samples such as the Kaidun CM lithology (measured over two sessions), NWA 7542A and B which are different thin sections of the same meteorite, and the linked howardite PRA04401 and 04402.

Meteorite	Meteorite type	Type/clast type	⁵³ Mn/ ⁵⁵ Mn	Age (Ma)		
Carbonaceous chondrites						
Ivuna	CI chondrite	-	$2.78e^{-6} \pm 5.10e^{-7}$	4562.1 0.9/1.1		
Alais	CI chondrite	-	$3.68e^{-6} \pm 6.40e^{-7}$	4563.6 0.9/1.0		
Orgueil	CI chondrite	-	$3.13e^{-6} \pm 8.40e^{-7}$	4562.7 1.3/1.7		
LON 94101	CM chondrite	-	$4.80e^{-6} \pm 6.60e^{-6}$	4565.0 4.6/4.7		
C1 clasts						
DaG 319	Ureilite (C1a)	C1	$-3.41e^{-6} \pm 4.30e^{-6}$	no age		
Sahara 98645	H3	C1	$-7.78e^{-6} \pm 7.30e^{-6}$	no age		
Kaidun (2)	C _{ung} chondrite	C1	$2.89e^{-6} \pm 4.10e^{-7}$	4562.3 0.7/0.8		
CM-like clasts						
Kaidun1	Cung chondrite	СМ	$4.66e^{-6} \pm 1.20e^{-6}$	4564.8 1.2/1.6		
Kaidun1_apr	C _{ung} chondrite	СМ	$3.84e^{-6} \pm 7.80e^{-7}$	4563.8 1.0/1.2		
Kaidun1 combo	C _{ung} chondrite	СМ	$3,44e^{-6} \pm 6.20e^{-7}$	4563.2 0.9/1.1		
NWA 7542 A	Eucrite p-mict	СМ	$2.02e^{-6} \pm 6.40e^{-6}$	4560.4 7.6/7.0		
NWA 7542 B	Eucrite p-mict	СМ	$-1.52e^{-5} \pm 1.60e^{-5}$	omitted		
PRA 04401	Howardite	СМ	$6.53e^{-6} \pm 4.10e^{-6}$	4566.6 2.6/5.3		
PRA 04402	Howardite	СМ	$1.40e^{-6} \pm 6.70e^{-5}$	4558.4 9.4/9.2		